THE MANTLE SOURCES OF MARE BASALTS: LIGHT LITHOPHILE ELEMENT MODELLING OF THE MAGMA OCEAN AND LOW-Ti BASALTS.

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We have used light lithophile elements (Li, Be), in conjunction with other trace elements, to model the sources of the low-Ti mare basalts. In contrast to high-Ti mare basalt sources, which contain from 0.8 to 1.5% trapped residual magma ocean liquid, low-Ti mare basalt sources appear to be relatively devoid of this incompatible-element-enriched trapped liquid (<0.5%). Source modelling indicates that the low-Ti basalts were melted from sources formed after 82-94% crystallization of an early moon-wide magma ocean, in contrast to high-Ti basalts which were formed from more evolved magma ocean cumulates (after about 95% crystallization). All mare basalts were melted from the uppermost 20% of the magma ocean cumulate pile, whereas volcanic glass beads could have come from the lower mantle.

INTRODUCTION TO LMO MODELLING -- Hughes et al. [1-2], Snyder et al. [3], and Snyder and Taylor [4] presented models for evolution of the lunar magma ocean (LMO) with an initial starting composition for most lithophile trace elements that was approximately 3x chondritic. Whereas the LMO cumulate sources for mare basalts are likely located in the upper 25% of the upper mantle [5], we have modelled the composition of these sources by combining olivine-pigeonite-clinopyroxene adcumulates with variable proportions of trapped residual LMO liquid. Unlike the high-Ti mare basalts which indicate 0.8 to 1.5% trapped liquid in the source, low-Ti sources are relatively depleted in trapped residual liquid. The source of the Apollo 12 ilmenite basalts had less than 0.2% trapped liquid in the cumulates and the olivine and pigeonite basalts were derived from a similar source with 0.4 to 0.5% trapped residual liquid [5].

LIGHT LITHOPHILE ELEMENT MODELLING -- We have included the light-lithophile elements Li and Be in our LMO modelling [5]. The light lithophile elements (Li, Be, and B) are an important class of elements for the study and modelling of magmatic processes on the Moon. Norman and Taylor [6] presented evidence that the Li-REE systematics of mare basalts and highlands crustal rocks "track the evolution of the Moon's crust and mantle during crystallization of the magma ocean." Li behaves as a moderately incompatible, and B and Be as highly incompatible elements in mafic systems [7-9].

In order to calculate the initial LMO composition, we again assumed that ~30% of the bulk Moon (composition from [10]) was partially melted leaving an olivine-orthopyroxene residue (mineral/melt partition coefficients for olivine and orthopyroxene from [11]). Thus, the initial LMO contained 1.80 ppm Li and 0.52 ppm Be.

The Li-Be systematics of seven fine-grained basalts have been determined from the Apollo 12 collection by ICP-MS [12] (Fig. 1). Olivine basalts typically have the lowest Li (4.5 to 7.5 ppm) and Be (~0.9 ppm) abundances, whereas pigeonite and ilmenite basalts overlap at higher abundances (6.1 to 8.4 ppm, and 1.1 to 1.9 ppm, respectively)[5]. Beryllium abundances of the fine-grained olivine basalts were found to be lower than those in the pigeonite and ilmenite basalts, consistent with previous analyses.

The Li/Yb ratios of Apollo 12 low-Ti basalts are unique with similar values of ~2, at Li abundances from 6.7 to 10.8 (Fig. 2: filled circles from [13], filled stars [5]). Other low-Ti basalts from Apollo 15 generally have higher Li/Yb ratios (~3). High-Ti mare basalts from the Apollo 11 and 17 sites have Li/Yb ratios of ~1 (Fig. 2). Picritic glasses from all landing sites, excluding Apollo 12, have Li/Yb ratios in excess of 3 [11]. Highlands rocks, which are generally enriched in plagioclase with a high Li/Yb ratio, also have Li/Yb values in excess of 3 (and up to 100) along with Li abundances of < 8 ppm [6]. Li/Yb ratios of KREEP are ~1, but with Li abundances in excess of 20 ppm (Fig. 2).

Fig. 1

Fig. 2

Li AND Be MODELLING OF LOW-Ti MARE BASALTS: G.A. Snyder, C.R. Neal, and L.A. Taylor
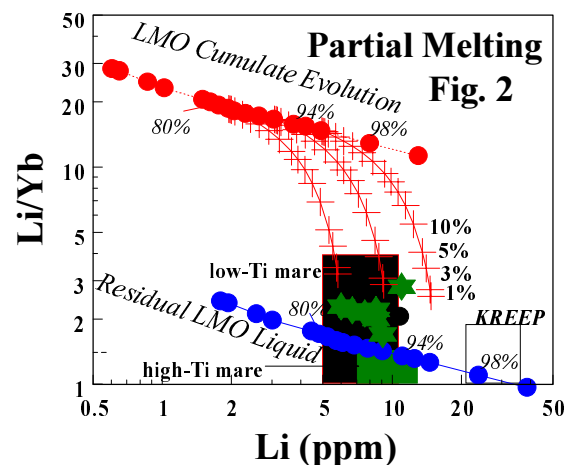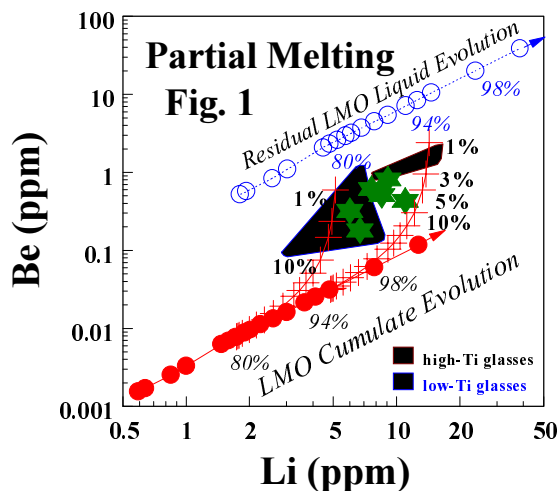
Li-Be systematics of Apollo 12 fine-grained basalts suggest that they are derived by partial melting of cumulate sources after 80% and 94% crystallization of the LMO (Figure 1). In fact, the Apollo 12 basalts indicate from 2% to 5% partial melting of upper mantle cumulate sources. Even lower degrees of partial melting of upper mantle cumulate sources are indicated when the REE are modelled relative to Li (Fig. 2). Partial melting of cumulate sources formed after 80% to 94% crystallization of the LMO will generate parental magmas that can fractionate to give all low-Ti mare basalts. Residual LMO liquids after approximately 98% crystallization yield compositions similar to postulated urKREEP.

UPPER VERSUS LOWER MANTLE SOURCES FOR MARE MAGMAS -- We have shown above that the upper mantle source for the ilmenite basalts was likely formed in the magma-ocean cumulate pile significantly earlier than that of the high-Ti mare basalts, and that ilmenite is not required in the source [14,15]. This might suggest that the ilmenite-bearing source was localized only in the region beneath Mare Serenitatis and Mare Tranquillitatis, in the eastern near-side. However, analyses of picritic glasses from all landing sites [11,16] have shown the proclivity for these samples to be high-Ti in tenor. Even picritic glasses retrieved from notably low-Ti mare sites, like Apollo 12 and Apollo 15, have high-Ti abundances.

There is abundant evidence that the mare basalts from a given landing site are notably dissimilar in their trace-element signatures to picritic magmas, represented by glass beads, from the same site [17]. The Li and Be abundances in fine-grained, low-Ti basalts (6.0 to 11 ppm, and 0.18 to 0.81 ppm, resp.) from Apollo 12 are vastly different from the abundances in the high-Ti (15.8 to 16.7 wt% TiO_2) "red" volcanic glasses (19.2 ppm Li and 1.14 ppm Be) from the same landing site [11,16]. In fact, the Li and B abundances in this Apollo 12 red glass are the highest of any lunar picritic glasses yet analyzed [11]. It is likely that these elevated Li and Be abundances for Apollo 12 red glasses indicate derivation from volatile-undepleted lower mantle (e.g., [18]).

Mare basalts with elevated Ti contents are thought to be the consequence of melting of ilmenite-bearing layers formed late in the crystallization of the lunar magma ocean. The lower mantle of the Moon should be relatively undifferentiated, composed of mostly olivine and orthopyroxene and extremely poor in ilmenite. If this is so, one would not expect picritic magmas, which come from the lower mantle, to have high Ti contents, especially picritic magmas that extruded at landing sites (like Apollo 12 and 15) where there is little evidence of high-Ti mare volcanism. How might primitive picritic magmas attain this high-Ti signature?

The high-Ti nature of many picritic magmas (as evidenced in picritic glass beads) either must have been inherited from the source region or introduced after initial melting in the source region. Ringwood and Kesson [19] first suggested and Spera [20], Hess and Parmentier [21], and Hess [22] further developed the idea that ilmenite-bearing portions of the lunar upper mantle, due to density contrasts, will sink until they form a lunar core. They also consider it likely that some of this ilmenite will mix with the lunar mantle, thus creating fertile high-Ti source regions throughout the mantle. The depth of incipient melting for high-Ti picritic glasses could be much greater than 400-500 km [22], especially if one considers that picritic magmas were formed by polybaric fractional fusion [23]. Therefore, high-Ti picritic magmas could be formed at a variety of depths throughout the lunar lower mantle.

However, Snyder and Taylor [24] have indicated several problems with the convective overturn hypothesis and consequent sinking of an ilmenite layer. Furthermore, Wagner and Grove [25] have shown that high-Ti picritic magmas could have been generated up to 1000 km deep in the lower mantle of the Moon, and then assimilated ilmenite from ilmenite-bearing layers in the upper mantle of the Moon, during transit to the surface. Therefore, it is still considered possible that the initial layering produced by crystallization of a lunar magma ocean has been preserved, at least on a regional scale [4], in the upper mantle of the Moon.

SUMMARY -- Chemical modelling of the crystallization of an incipient lunar magma ocean has allowed us to place constraints on the nature and location of the upper mantle sources for the low-Ti basalts. In contrast to high-Ti mare basalt sources, which contain from 0.8 to 1.5% trapped residual magma ocean liquid, low-Ti mare basalt source appear to be relatively devoid of this incompatible-element enriched trapped liquid (<0.5%). The low-Ti basalts were melted from sources formed after 82-94% crystallization of an early moon-wide magma ocean, in contrast to high-Ti basalts which were formed from more evolved magma ocean cumulates (after about 95% crystallization [3]). It appears that all mare basalts were melted from the uppermost 20% of the magma ocean cumulate pile.

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